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RESIDUAL ACCELERATION DATA ON IML-1: DEVELOPMENT OF A DATA REDUCTION AND DISSEMINATION PLAN

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1. Introduction and General Status

The work performed under NASA Grant NAG8-759 is geared towards the development of a residual acceleration data analysis plan that will allow principal investigators of low-gravity experiments to efficiently process their experimental results in conjunction with accelerometer data. Our basic approach has consisted of the following program of research.

1. Identification of sensitive experiments and sensitivity ranges by order of magnitude estimates, numerical modelling, and investigator input.
2. Research and development towards reduction, supplementation, and dissemination of residual acceleration data.
3. Implementation of the plan on existing acceleration data bases.

During the fifth semi-annual period we have concentrated on outlining our two-tier data processing plan and distributing it to interested investigators. With the first flight of SAMS during this period, we have begun to investigate appropriate methods to access the SLS-1 data base. These data access procedures will also be used to acquire STS-32 HISA data and IML-1 ground test data.

Specific details of our progress during the fifth semi-annual period will be given in the following sections: section 2 - identification of IML-1 principal investigators interested in analyzing accelerometer data; section 3 - data processing; section 4 - implementation of the processing plan on existing data bases; section 5 - future work.

2. Identification of Sensitive Experiments

We have identified several IML-1 experiments as potentially sensitive to variations of the residual acceleration environment. In addition, several other IML-1 principal investigators have expressed an interest in obtaining acceleration information to use in their post-flight experiment analysis. The following is a list of the experiments concerned.

- CPF - Critical Point Facility
- FES/CAST - Casting and Solidification Technology
- FES/TGS - Crystal Growth from Solution

- GPPF - Gravitational Plant Physiology Facility
- MICG/VCGS - Growth of Mercuric Iodide from Vapor
- OCGF - Organic Crystal Growth Facility
- PCG - Protein Crystal Growth

The principal investigators of these experiments have been contacted for their assessment of their acceleration data processing needs. We sent the investigators a brief description of our two-level data processing plan and a short questionnaire about their experiment timeline and their experiment sensitivity to accelerations, see **Appendix A**. For each experiment, we included our assessment of the experiment sensitivity, general suggestions on windows of acceleration data to analyze, and examples of data presentation styles. We expect to use the responses to these questionnaires to supply more specific suggestions about the type of post-flight data processing that would be most appropriate for each experiment.

3. Data Processing

Our research and development towards a plan for reduction and analysis of residual acceleration data has continued on several fronts during the fifth semi-annual period. In the process of developing a data reduction plan, we have investigated several data processing techniques and data presentation styles. In addition, we have begun to use pattern recognition techniques to analyze residual acceleration data. This work will help identify and group acceleration disturbances that may be of interest to investigators.

<u>Data Processing Plan</u>: We have developed a two-tiered data processing plan. Details of this plan are given in a paper to be printed in <u>Microgravity Science and Technology</u>: **M. J. B. Rogers and J. I. D. Alexander, Residual Acceleration Data Analysis for Spacelab Missions.** A preprint of this paper is included in **Appendix B**. We will also be discussing data processing at the <u>AIAA 30th Aerospace Sciences Meeting</u>: **M. J. B. Rogers and J. I. D. Alexander, Experiment Specific Processing of Residual Acceleration Data.** In

addition, discussions of the processing plan and our work to date have been presented to the microgravity community through participation in Microgravity Measurement Group (MGMG) meetings and the April 1991 International Workshop on Vibration Isolation Technology for Microgravity Science Applications: **M. J. B. Rogers, Development of a Residual Acceleration Data Reduction and Dissemination Plan.**

Data Presentation: In addition to basic time history and frequency domain plots, we would like to present various aspects of accelerometer data so that the low-gravity environment during a given time window can be easily understood. One simple way of presenting an overview of the acceleration level in a particular time window is to show the amount of time the data exceed certain limits. This may be done by a simple pie chart showing the percentage of points with magnitudes larger than specific limits and it may also be done by plotting a time history of the occurrences of data greater than some limit, see Figs. 1 and 2. This second method provides a much cleaner time history plot than a plot of the entire data window, and should be easier to interpret.

Another useful overview of the data is provided by an amplitude-frequency-time plot, see Fig. 3. This type of plot shows the amplitude spectra (or power spectral densities) of successive windows of data so that the investigator can see at what time certain frequency disturbances were excited. This should be useful for correlating acceleration data with experimental results when regularly sampled, numerical experiment output is not available.

Data Processing Techniques: The data processing techniques evaluated during this period include wavelet transformation and ensemble averaging. Wavelet theory is a relatively new processing technique that can be used in analyzing signals that change rapidly (Bijaoui, et al., 1989; Kronland-Martinet, et al., 1987; Tuteur, 1988). Wavelet analysis can provide information about the location of features within a data set and can detect and highlight the onset of sudden changes in data character. At this time we are still evaluating the possibility of introducing wavelet theory to the analysis of residual acceleration data.

Ensemble averaging is a comparatively old data analysis technique in which a series of successive data windows are transformed into the frequency domain and their spectra are averaged to get a general representation of the frequency content of the entire data window (Franke, et al., 1990; Karl, 1989). As the number of segments a data window is separated into is increased, the statistical estimation errors inherent in time series analysis are decreased. This decrease occurs at the expense of frequency resolution. Despite the decrease in frequency resolution, this technique is useful for obtaining a general idea of the frequency content of a relatively long data window and provides a nice complement to an amplitude-frequency-time plot of the same window.

Pattern Recognition: Pattern recognition is the process of assigning discrete packets of information about a particular phenomenon to a group of subsets which partition the associated sample space (Tou and Gonzalez, 1974). For example, an optical character reader is a pattern recognition system; the characters of an alphabet define the partitions and the letters of the scanned text are the discrete packets of information to be processed. The recognition process assigns letters read by the scanner to the characters of the alphabet.

There are many ways that pattern recognition may be accomplished. In the simplest pattern recognition problem, a list associates each pattern with its respective class. In this situation, the pattern recognition process consists of receiving the unknown pattern, looking through the list for the class associated with that particular pattern (which is guaranteed to be in the list), and then declaring the pattern to be recognized and displaying the associated class. Unfortunately, this situation is almost never applicable. Usually, there is an infinite (or effectively infinite) number of patterns or the list that maps pattern to class is unknown. Such is the case when the number and/or composition of the classes is unknown.

A more realistic situation occurs when there is a common property associated with some patterns and, while the direct mapping from pattern to class is unknown, there is a known mapping from common property to class. The problem of pattern recognition is thus reduced to a two step process. One first determines the particular value of the common property associated with an unknown pattern and then determines the class associated with that common property. This classifies the pattern.

A third method used for pattern recognition is clustering (Dubes and Jain, 1976). This method uses the geometric arrangement of pattern vectors to classify the data. Clustering routines attempt to divide input information into a number of classes so that the distances between the points within any given cluster are minimized according to some distance measure while the distances between the various clusters are maximized by some other distance measure. This theoretically causes similar patterns to fall into the same class and partitions the pattern space into the most appropriate number of clusters.

A fourth method for pattern recognition is syntactic pattern recognition. This method uses formal language theory to recognize patterns and is best suited for use when the primitives of the input information are known and the language is predetermined.

In general, the clustering method appears to be best suited for use in determining the origin of acceleration vectors on orbiting space laboratories. In particular, clustering appears to offer the possibility of determining the proper number of clusters for each time window. This, in turn, may allow the use of syntactic pattern recognition because determination of classes is equivalent to a knowledge of primitives.

During the fifth semi-annual period we have begun to apply the clustering method of pattern recognition to Spacelab 3 (SL3) acceleration data by implementing the ISODATA clustering algorithm and a variant of the ISODATA algorithm called CLASS (Fromm and Northouse, 1976). ISODATA is a clustering algorithm which uses heuristics to aid in the search for an appropriate configuration of clusters. Simply put, given an arbitrary number of start clusters, ISODATA will split clusters whose standard deviation along an orthogonal axis exceeds some predetermined value. It will also merge pairs of clusters with intercluster distances less than some predetermined value. ISODATA is run interactively with the user modifying various predetermined values as the program runs through iterations. We have determined that ISODATA is probably unsuited to be the primary means of clustering the SL3 data because of the large amount of data involved. ISODATA will be used, however, for confirmation of clustering determined by other means.

The CLASS modification of ISODATA shows more promise for initial identification of clusters. CLASS automates the selection of the predetermined values of ISODATA and appears to converge very rapidly to the correct number of clusters for large data sets. Independent confirmation of these results is needed. This will be achieved using a test data set and a program which has the capability to determine validity of clusters (Bailey and Dubes, 1982).

4. Implementation on Existing Data Bases

The majority of our processing to date has been done with SL3 accelerometer data. During the fifth semi-annual period, we obtained accelerometer data from STS-32 (Honeywell In-Space Accelerometer, HISA). We will be processing this data in much the same way we expect to process IML-1 flight data. The HISA data will be analyzed using sensitivity limits computed at CMMR for a liquid bridge experiment similar to that flown with the HISA (Zhang and Alexander, 1990; Alexander and Zhang, 1991). We would like to note that processing of the HISA data is being undertaken with advice from Jeff Schoess of Honeywell.

We are also anticipating the release of the SAMS data from the SLS-1 (STS-40) mission. The majority of the mission video downlink was recorded by ACAP and both ACAP and SAMS personnel logged the occurrences of significant events, so, despite several deactivations of SAMS during the mission, the correlation of the data with the mission timeline should be fairly complete.

5. Future Work

As we approach the launch of IML-1, we will spend the remainder of the third annual period of NAG8-759 designing specific data processing plans for the interested principal investigators. We intend to discuss the questionnaires that were distributed to the investigators during IML-1 mission simulations in the fall.

We will also continue to assess data processing and presentation techniques. In particular, we will continue the development and testing of pattern recognition routines to use with acceleration data. Specific patterns identified using these techniques may be useful as a basis for wavelet analysis as discussed earlier.

6. References

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7.28 Minute Long Time Window from EET 67:44:44.000
Percentage of Total Acceleration Magnitude in Specified Magnitude Ranges

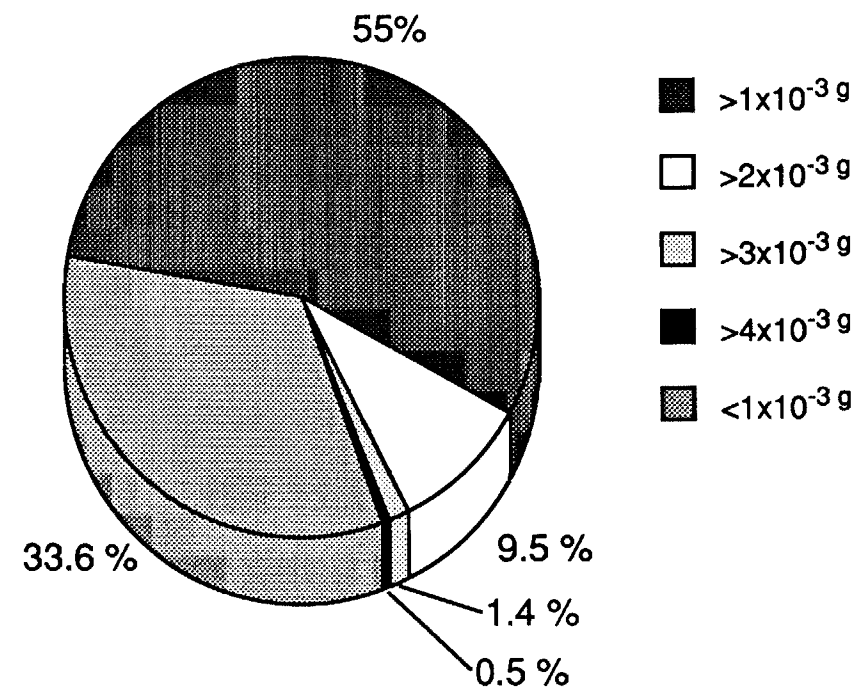


FIG. 1

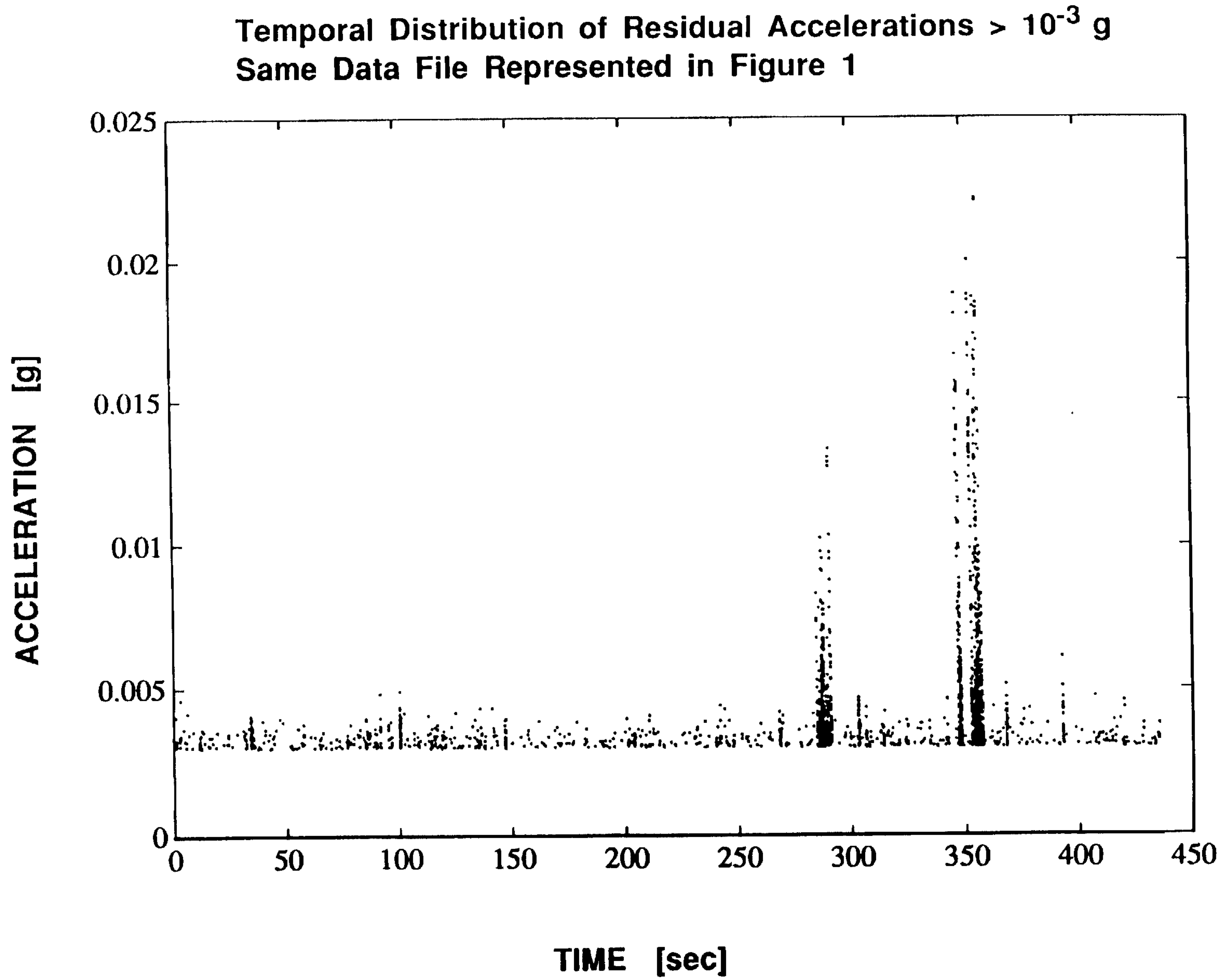
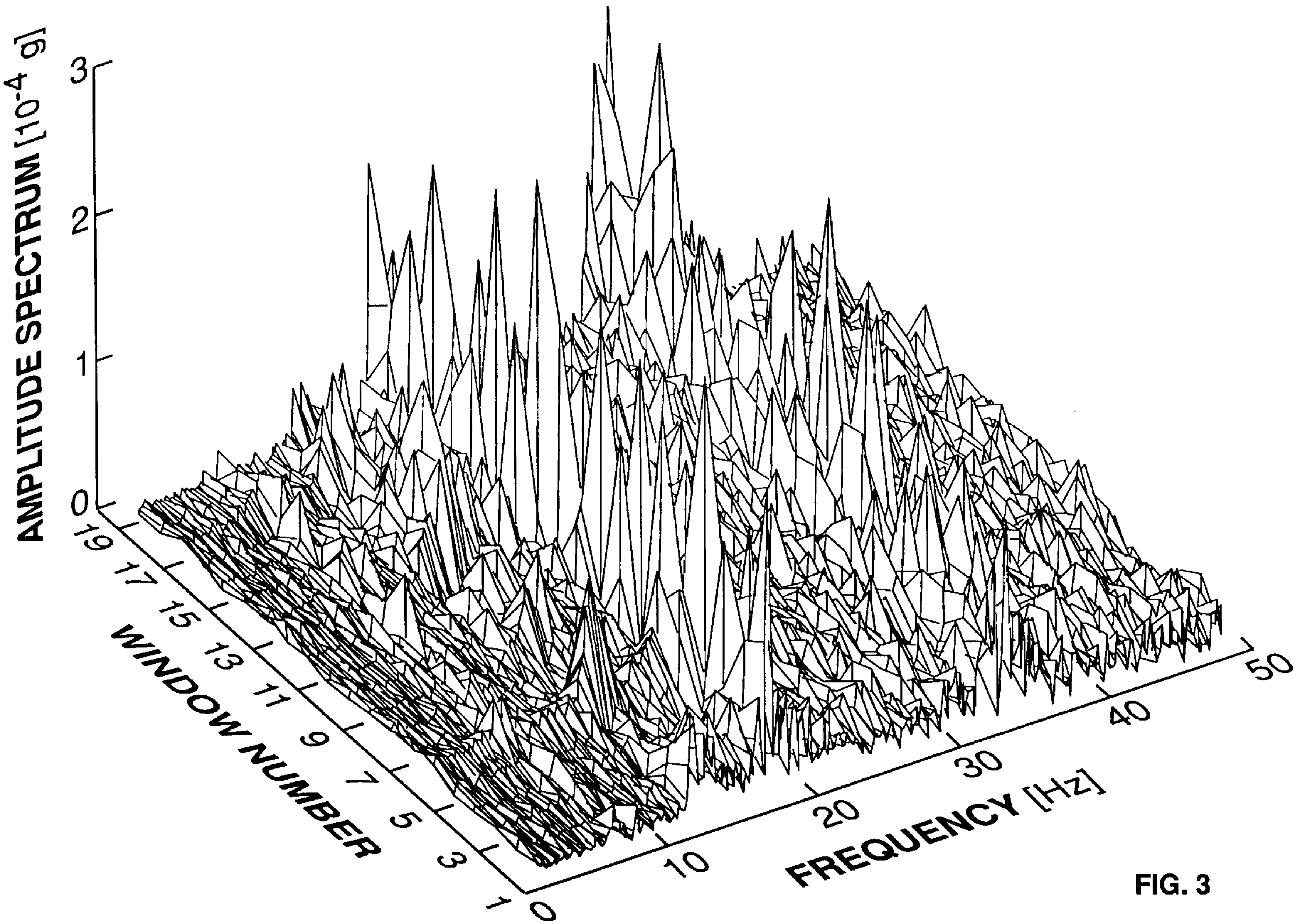

Temporal Distribution of Residual Accelerations > 10^{-3} g
Same Data File Represented in Figure 1
0.025
0.02
0.015
0.01
0.005
0
ACCELERATION [g]
0
50
100
150
200
250
300
350
400
450
TIME [sec]

FIG. 2



AMPLITUDE SPECTRUM [10-4 g]
0
1
2
3
WINDOW NUMBER
1
3
5
7
9
11
13
15
17
19
FREQUENCY [Hz]
0
10
20
30
40
50

FIG. 3

Appendix A - Principal Investigator Questionnaire

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ACCELERATION DATA ANALYSIS PLAN

(SUGGESTED APPROACH TO ACCELERATION DATA ANALYSIS)

EXPERIMENT: *«experiment»*

PRINCIPAL INVESTIGATOR: *«pi»*

ADDRESS: *«address1»*
«address2»
«address3»
«address4»

TELEPHONE: *«phone»*
FACSIMILE: *«fax»*

GENERAL DESCRIPTION

PRE-FLIGHT PLAN - The initial phase of the data reduction plan involves the identification of factors which can be used to limit the quantity of data that needs to be supplied to a principal investigator. Answers to the attached questions will enable the investigator to select short windows of data to analyze for an overview of the low-g environment during their experiment. Initial analysis of such windows, in conjunction with experimental results, will allow the principal investigator to identify interesting windows of data to analyze in more detail.

POST-FLIGHT PLAN - We suggest that the investigator initially evaluate ten windows of acceleration data from the time of the experiment. These windows should be spaced as is most appropriate for the experiment, i.e. during times of increased sensitivity or during known disturbances. The remaining windows should be as evenly distributed (temporally) as possible. The length of the windows should also be selected to be as appropriate to the experiment as computer limitations will allow. That is, some investigators will be able to analyze hour long windows, but this capability does not necessarily mean that analyzing windows of that length will be most appropriate for their experiment analysis needs. Some knowledge of the nature of experiment response to acceleration sources is important for selecting window length.

Specific windows of interest to the investigator can be identified using a threshold detection routine based on the experiment acceleration sensitivity. The use of a threshold detection routine should give some indication of the appropriateness of the sensitivity limits used. If the limits are exceeded the majority of the time, an initial look at the experimental results should indicate whether the acceleration environment was too severe for the experiment or whether the tolerance limits were too strict. Similarly, if the limits are rarely exceeded, analysis of the experimental results should indicate whether the sensitivity limits used were too relaxed or whether the acceleration levels were low enough for a successful experiment run and sensitivity limits should be modified.

Additional windows of interest can also be identified from initial analysis of experimental results. Windows can be chosen around times when the experiment shows unexpected results suspected to be related to perturbations in the low-gravity environment.

ACCELERATION DATA ANALYSIS PLAN

(SUGGESTED APPROACH TO ACCELERATION DATA ANALYSIS)

EXPERIMENT:	*«experiment»*
PRINCIPAL INVESTIGATOR:	*«pi»*
ADDRESS:	*«address1»* *«address2»* *«address3»* *«address4»*
TELEPHONE:	*«phone»*
FACSIMILE:	*«fax»*

PRE-FLIGHT PLAN - Answers to the following questions will be used to select short windows for an overview of the low-gravity environment.

TIMESPAN OF EXPERIMENT:

LENGTH OF EXPERIMENT:

EXPERIMENT LOCATION:

SAMS SENSOR HEAD OF INTEREST, IF KNOWN:

NUMBER OF ACCELEROMETER DATA POINTS PER AXIS TO BE COLLECTED DURING EXPERIMENT (i.e., length of experiment (seconds) × sampling rate)

TIMES/REASONS OF KNOWN INCREASED EXPERIMENT SENSITIVITY:

DO YOU KNOW OF ANY POTENTIAL ACCELERATION SOURCES DURING YOUR EXPERIMENT? (eg, scheduled orbiter attitude adjustment)

ORIENTATION OF PRIMARY EXPERIMENT AXES WITH RESPECT TO ORBITER STRUCTURAL AXES:

POST-FLIGHT PLAN - For your experiment, we suggest analysis of data windows as indicated.

Additional specific windows of interest to the investigator can be identified using a threshold detection routine based on the experiment acceleration sensitivity. Based on analysis of your experiment, we suggest that the following sensitivities are appropriate for your experiment.

1. Frequency and magnitude ranges of interest:

2. Overall maximum tolerable acceleration magnitude
    a) Maximum continuous (steady) tolerable acceleration

    b) Maximum tolerable acceleration (peak detection threshold)

3. Experiment sensitivity to changes in acceleration orientation.

ADDITIONAL COMMENTS

The following are examples of plots that can be created from the type of data windows investigated.

1. Total acceleration magnitude of the three axes of accelerometer data:

$$a=(a_1{}^2 + a_2{}^2 + a_3{}^2)^{1/2}$$

2. The three axes of accelerometer data, a_1, a_2, a_3

3. Combined amplitude spectrum. Total magnitude of the amplitude spectra of the three axes of data.

4. Combined power spectral density. Total magnitude of the power spectra of the three axes of data. Detail out to 20 Hz.

5. The amplitude spectra of the three axes of data. Detail out to 20 Hz.

6. Direction cosine θ_x for the time window of interest. Detail of 100 seconds.

$$\theta_x = \text{acos}(a_1/a)$$

7. Amplitude spectra of twenty successive time windows. Detail out to 50 Hz.

8. Percentage of time analyzed that acceleration magnitude was in certain range of values.

NOTE:

- EET: Experiment Elapsed Time
- Spectral representations can be plotted out to any frequency less than the Nyquist.
- For plots shown, sampling frequency is 300 Hz.
- Details of analysis techniques will be supplied upon request.

The plots shown here are examples of how a principal investigator may want to present residual acceleration data relevant to their experiment. Not all of the data representations will be desirable to all investigators. In particular, only one of the spectral presentations shown here will most likely be useful to a given investigator. These representations depict the relative strengths of the frequency components present in the window of interest, but have different dimensions and represent different aspects of the data.

The **Amplitude Spectrum** obtained for a time series using the Fourier transform indicates the frequencies of the sine and cosine terms that make up the signal being studied. For the time period considered, the Fourier transform at a given frequency is an average of the components of the time series that have that frequency and has the dimensions of the original time series.

The **Power Spectral Density** has dimensions of (units of original data)^2/Hz and indicates the power or energy present in the series per unit frequency interval, i.e., the square root of the area under the power spectral density plot for a given frequency interval represents the RMS value of the input time series for that frequency range.

Appendix B - Accepted for publication in Microgravity Science and Technology

Residual Acceleration Data Analysis for Spacelab Missions

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Abstract

Materials processing and life sciences experiments are being conducted in earth orbiting laboratories to take advantage of the reduced gravity environment of space. Accelerometer data are collected during low-g missions to describe the acceleration environment, but the amount collected per mission is overwhelming (on the order of gigabytes). Different research goals, sensor types, and processing techniques make it difficult to compare acceleration data plots from different missions. In particular, spectral representations of data differ widely. Specific structural modes are known for the Orbiter and Spacelab from engineering models and ground tests, but a complete characterization of primary and secondary acceleration sources has not yet been compiled.

We have developed a two level data reduction plan that will allow investigators to create limited, user specific accelerometer data bases that can be used in post-flight experiment analysis and orbiter characterization. First level processing uses our knowledge of experiment sensitivity to identify times when tolerable acceleration levels are exceeded. Together with a preliminary analysis of experiment results, this enables the experimenter to identify particular time intervals which require more detailed processing. Second level analysis centers on acceleration time histories (magnitude and orientation) and frequency components. Data decimation is introduced as a means for reducing the amount of data that must be processed while analyzing a given time window. Cross-correlation analysis is

discussed; it is useful in post-flight experiment analysis for assessing causal relationships between residual accelerations and experimental responses. The ability to identify and process limited windows of acceleration data will further the acceleration environment characterization process and will be essential in revising the design, location, and use of low-gravity experiment equipment for future missions.

1. Introduction

In recent years, low-gravity experimenters have shown increased interest in obtaining residual acceleration data to use in pre-flight modelling and post-flight processing of their experiments. The object of many low-gravity materials processing and life sciences experiments is to study physical and biological phenomena in space under drastically reduced acceleration conditions relative to the steady 9.8 ms^{-2} (1 g) acceleration experienced on the earth's surface. Because some of these experiments are sensitive to even small magnitude accelerations [1-5], it is necessary to characterize the time-dependent acceleration environment in order to properly interpret the experimental results. To date, one of the major factors that have prevented investigators from accessing residual acceleration data for post-flight experiment analysis and orbiter characterization is the vast amount of data that results from a typical orbiter mission. Even for a sampling rate as low as 12.5 Hz, on the order of 10^6 samples per axis can be expected from a seven day low-gravity mission.

In the following section, we discuss residual acceleration measurements that have been reported in the literature and suggest reasons for the differences in magnitude among the various data bases. In section 3, we introduce various aspects of the Orbiter characterization process and in section 4 we present several specific techniques that investigators can use in the post-flight processing of residual acceleration data and experimental results.

2. Residual Acceleration Data

Measurements of residual acceleration have been collected during several Orbiter missions with a variety of instruments [6-13]. The resulting data, supplemented by the simulation of orbiter attitude motion accelerations, have provided us with a general idea of the low-gravity environment aboard an Orbiter during a typical mission. Specific acceleration sources, however, are still difficult to characterize. In general, three categories of residual accelerations are experienced in orbiting space laboratories: quasi-steady, transient, and oscillatory [9,14]. The quasi-steady accelerations are related to the Earth's gravity gradient, spacecraft attitude and altitude, and atmospheric drag. They have frequencies on the order of the orbital frequency (10^{-4} Hz) and magnitudes in the 10^{-9} to 10^{-6} g range [9,12,14]. 10^{-6} g accelerations have been recorded using specialized accelerometer systems such as HiRAP [13], but these quasi-steady accelerations have yet to be successfully identified in data recorded with conventional systems because of instrument limitations and the relative strength of higher magnitude and higher frequency accelerations [15].

These higher magnitude, higher frequency accelerations constitute the other categories of residual accelerations. Transient accelerations can have magnitudes as large as 10^{-2} g and tend to vary considerably in orientation, but such disturbances are rarely sustained for more than a fraction of a second [11]. These accelerations can be caused by both crew related and operational activities, Figs. 1 and 2. Oscillatory accelerations have magnitudes comparable to transient accelerations (10^{-5} to 10^{-3} g), fluctuate rapidly in orientation, and are experienced over a broad range of frequencies for longer times. Recorded oscillatory accelerations are generally related to machinery vibrations and rotations and to structural modes of the Orbiter excited by both transient and oscillatory sources. Frequency domain analysis of one second to fifteen minute long windows of Spacelab 3 (SL3) acceleration data indicates that, from 5×10^{-3} to 50 Hz, transient and oscillatory accelerations have amplitude spectra with maximum magnitudes no greater than 10^{-3} g, Figs. 1b and 2b [11,15].

When comparing acceleration measurements from different missions, it is important to note that few accelerometer systems have the same characteristics. Because of different research goals, sensor types, electronics, sampling rates, processing techniques, instrument locations, and other factors, comparisons among residual acceleration data plots presented in the literature are often difficult. The sampling rate, especially, can cause an appreciable magnitude difference among various sets of data [12]. Higher frequency data are constructively added to lower frequency data when high sampling rates are used. This results in overall higher magnitude readings than obtained with lower sampling rates. Similarly, analog filtering performed as part of the data collection scheme, as well as post-flight digital filtering, can result in different magnitude levels for different data sets, see Fig. 3.

The use of different processing techniques results in a variety of data presentation styles that may initially appear comparable. Time history plots vary considerably, however, and may include plots of individual axes of data, acceleration vector magnitude, RMS values, and integrated data. In addition, the data presented may be regularly sampled data, peak value data, or some specialized form of data [6-12]. Representations of residual acceleration data as a function of frequency can also take a variety of forms [15-18]. Most common are the amplitude and power spectral densities, see Section 4.2. If an investigator is only interested in the identification of dominant frequency components, then any type of spectrum is adequate. Meaningful comparisons of component magnitudes among various plots or between spectra and sensitivity plots, however, require a standardized spectral density format.

Instrument location is another important factor involved in comparative data analysis. Data collected near a dominant acceleration source (motors, fans, areas of high crew activity) will show higher overall acceleration levels than data collected with an equivalent system located at a distance from such sources. Some interest has been expressed by low-g investigators in evaluating the propagation of accelerations from known sources through various structures of an Orbiter [19]. This is an important factor in Orbiter characterization, and in the identification of especially noisy systems and appropriate sites for low-gravity experiments.

3. Orbiter Characterization

Limited attempts have been made to date to construct a characterization of the low-gravity environment of the shuttle Orbiters [6-11,15]. Specific structural modes are known for the Orbiter and Spacelab from engineering modelling and ground testing, see Table 1 [9,12,19,20]. The excitation of these modes has been identified in residual acceleration data as associated with thruster firings and crew activity within the Spacelab [7,9,11,12,15].

Both Orbiter and Spacelab structural modes exist around 5 Hz and 7 Hz [9,12]. An 12 Hz component observed in the data represents an Orbiter structural mode excited by shuttle operations [12]. An ubiquitous 17 Hz signal, present in accelerometer data recorded by different systems, represents another Orbiter structural mode as well as the dither frequency of the KU band communications antenna [11]. Figures 1 and 2 show the presence of these specific frequency components in SL3 data.

A difficulty that will continue to hamper Orbiter characterization attempts is that no acceleration source acts alone. Orbiter maneuvers involve the firing of multiple thrusters in a sequence of pulses and experiment manipulation involves the handling of various pieces of equipment. These transient acceleration sources occur in addition to the background accelerations related to numerous mechanical systems active during a mission. Figure 4 shows the dynamic nature of the Spacelab environment. The spectral densities of twenty successive time windows are shown. It can be seen that, while there are dominant frequency components consistently present, the relative strengths of specific components vary over time.

The active environment of the orbiting laboratory does not mean, however, that the task of Orbiter characterization is impossible. Through a sequence of ground-based and in-space tests of the response of specific structures to known acceleration sources, we can eventually construct a catalogue of characteristic accelerations and acceleration levels in particular areas of the space laboratory [19,20]. A knowledge of the acceleration environment to be expected during a mission and of the acceleration levels expected in specific locations in an Orbiter will allow the development and siting of future experiments to best utilize or avoid specific aspects of the low-gravity environment.

4. Post-flight Data Analysis

As stated earlier, one of the major obstacles encountered in the analysis of residual acceleration data is the amount of data resulting from a single mission. Gigabytes of accelerometer data are expected from most flights of the NASA Space Acceleration Measurement System (SAMS). In an attempt to effectively manage these data, we have developed an analysis plan that will allow principal investigators of low-gravity experiments to create limited, user specific data bases. The limited data base can be efficiently used in post-flight processing of experimental results. We are also analyzing various processing techniques that may be useful for more detailed residual acceleration data analysis. Two of these techniques, data decimation and cross-correlation analysis, are discussed later in this section.

4.1 Creation of Limited, User Specific Data Bases

In order to create user specific data bases, investigators must have some knowledge of the sensitivity of their experiments to the residual accelerations expected during flight. Such knowledge can be gained from pre-flight modelling of the experiment or from preliminary runs of the experiment in low-gravity conditions (drop-towers, sounding rockets, parabolic flights, orbital flights). Post-flight analysis of experimental results in conjunction with residual acceleration data will also be easier if appropriate experiment parameters are recorded during the experiment.

Our suggested approach to the reduction of residual acceleration data invokes a two level plan that uses sensitivity limits and preliminary experimental results. The plan is outlined in Table 2. Pre-flight identification of acceleration sensitivity of a particular experiment will determine acceleration frequency and magnitude ranges of interest and experiment tolerance limits [1]. Particular times when the experiment is most likely to be affected by residual accelerations can also be identified prior to the mission. This includes increased experiment sensitivity during certain stages (e.g., protein crystal growth during the nucleation stage) and expected experiment response to certain timelined mission operations (e.g., thruster firings and crew exercise periods). Preliminary post-flight analysis of experimental results will allow the investigator to identify times when unexpected results occurred that may be related to perturbations in the residual acceleration environment of the laboratory.

The second level of the data reduction plan involves the actual limitation and processing of the residual acceleration data base using the results of level one. A simple threshold detection routine can be used to identify times when the acceleration magnitude is greater than defined sensitivity limits. Windows of interest can also be selected based on the experiment and mission timelines and preliminary post-flight analysis. Timelines will indicate when sensitive stages of an experiment are scheduled and when potentially intolerable mission events such as Orbiter maneuvers are to occur.

4.2 General Processing Techniques

We have found that three main features of residual acceleration data can be used to characterize the acceleration environment of an orbiting space laboratory: the magnitude, direction, and frequency components of the residual accelerations in a given window. Time history information can be used to identify maximum and mean accelerations recorded per axis as well as various other statistics. The orientation of a residual acceleration vector can be estimated using direction cosines which give an indication of the angle between a measured acceleration and the recording axis. Because of the number of acceleration sources present in the Orbiter and the nature of oscillatory accelerations, the orientation of the residual acceleration vector tends to fluctuate with time [11]. See [16] for more details about evaluating residual acceleration magnitudes, orientations, and frequency components.

The frequency components of a window of residual acceleration data are computed using the Fourier transform. The spectral density obtained for a time series using Fourier analysis indicates the frequencies of the sine and cosine terms that make up the signal being studied. The spectral density of an axis of residual acceleration data a_λ is:

$$A_n = \frac{1}{N} \sum_{\lambda=1}^{N} a_\lambda \, e^{-i2\pi n\lambda/N} \tag{1}$$

where N is the number of points in the data window. For the time period considered, the spectral density at a given frequency is an average of the components of a_λ that have that frequency and has the dimensions of an acceleration [16-18].

The power spectral density of a window of data can be computed by:

$$P_n = 2TA_n^2 \tag{2}$$

where T is the length of the data window in time units. The power spectral density has dimensions of (units of original data)^2/Hz and indicates the power or energy present in the series per unit frequency interval. The square root of the area under the power spectral density plot for a given frequency interval represents the RMS value of the input time series in that frequency range [12,16,17].

Comparisons of spectral plots in the literature may be difficult because of differences in software involving scaling factors and definitions of spectra [17,18]. The two spectra discussed above are generally referred to as densities because they refer to a unit frequency interval. The use of a particular spectral representation often depends on the type of numerical analysis an investigator has planned. Because of the rather straightforward representation provided by equation (1), we advocate the use of this form. This spectrum gives frequency component magnitudes in units of acceleration. Most experiment sensitivity curves published to date are in the form of acceleration versus frequency, allowing ease of comparison for the time periods concerned [1]. In addition, the spectral density of equation (1) can be mathematically converted to a power spectral density by equation (2).

4.3 Data Decimation

Because of the high sampling rates used in the collection of residual acceleration data, detailed analysis is often limited to a minute or less of data. If an investigator is interested in processing long blocks of data (more than several minutes for sampling frequencies on the order of 100 Hz), an additional tool that can be used to limit data is data decimation which reduces the sampling rate [18,21-23]. Like any other data processing technique, some amount of caution must be practiced when decimating data, especially so that higher frequency data are not aliased into the lower frequency region of interest.

Figure 5 gives an example of data decimation applied to a window of SL3 accelerometer data. The original time series (Fig. 5a) is 65536 points long and has a maximum value of 1.28×10^{-2} g. The spectral density of this series out to 5 Hz is shown in Fig. 5b. Figure 5c shows the same window after the data were decimated 16 times; a 5 Hz lowpass filter was applied. This process reduced the number of points to 4096, while maintaining the temporal coverage of 218 seconds. Note, however, that the maximum acceleration level represented has decreased to 2.5×10^{-3} g. This occurs because the user has no control over data point selection - the sampling is periodic and the original extrema are not necessarily selected. The values of the spectral density of the decimated data are also decreased compared to the original spectrum. The general character of the data is maintained in both the time and frequency domains, so the impact of the decreased magnitudes on the post-flight analysis of accelerometer data depends on the specific needs of the investigator.

4.4 Cross-correlation Analysis

We are interested in analyzing the results of experiments run in a low-g environment. Cross-correlation techniques are generally used to determine the equivalence of time histories and to determine temporal relationships among time series. This appears to be, for specific experiment classes, a viable means of assessing causal relationships between residual accelerations and experimental responses to these accelerations. This analysis method is useful not only in situations where experiments are sensitive to high magnitude, transient accelerations, but also when experiments are most sensitive to oscillatory disturbances [24].

The cross-correlation of two time series can be written as:

$$\phi_{12}(\tau) = \int_{-\infty}^{\infty} f_1(t)\, f_2(t+\tau)\, dt \tag{3}$$

where f_1 and f_2 are two zero-mean time series and τ is a time lag. A normalized cross-correlation function is used when the time series considered are of different dimensions and/or comparisons are to be made among different sets of results. The normalized cross-correlation function is [17]:

$$\rho_{12}(\tau) = \frac{\phi_{12}(\tau)}{\left[\phi_{11}(0)\phi_{22}(0)\right]^{1/2}}. \tag{4}$$

The maximum value of the normalized cross-correlation function is unity, which indicates that the two time series considered are identical at the given lag; values close to zero indicate that there is very little similarity between the two series. Positive normalized cross-correlation values close to unity indicate good correlation and negative values with magnitudes close to unity indicate good correlation but with the series out of phase.

While the cross-correlation function between two time series can be estimated directly using equations (3) and (4), it can be estimated more efficiently by calculation of the cross-power spectrum:

$$\Phi_{12}(\omega) = F_1^*(\omega)\, F_2(\omega) \tag{5}$$

where F_1 and F_2 are the spectral densities of f_1 and f_2 and a superscript * denotes complex conjugation. The cross-power spectrum and cross-correlation function form a Fourier transform pair, so one can be easily obtained from the other. Estimation of the cross-correlation function of two series using the cross-power spectrum affords a factor of N/4p savings of computation time where $N=2^p$ is the length of the time series considered [22].

The application of cross-correlation techniques to the analysis of low-gravity experiments requires an experiment time history which represents parameters affected by variations of the low-gravity environment. Pre-flight modelling of experiments will enable the investigator to identify appropriate parameters to record. In the case that such a parameter cannot be recorded quantitatively, modelling may also be used to determine typical experiment responses to be used in the creation of experiment time series for cross-correlation analysis [1-5,24].

5. Summary

Investigators running experiments in the reduced gravity conditions of space need to be able to characterize the time-dependent acceleration environment in order to properly interpret their results. Characterization of the Orbiter acceleration environment to date has identified some Orbiter and Spacelab structural modes, Table 1 and Figs. 1-4 [9,12,19,20].

Because the amount of accelerometer data resulting from a typical Spacelab mission is on the order of gigabytes, we have introduced a data reduction and analysis plan with which investigators can merge pertinent segments of residual acceleration data into the post-flight analysis of their experiments. The two level data reduction plan is easily tailored to an investigator's needs based on mission and experiment timelines and information about the experiment sensitivity to accelerations. The first level of the plan involves identification of pertinent experiment time windows to study and the second level involves analysis of these windows. General data processing techniques that can be used include the analysis of time history statistics, acceleration vector magnitudes, and the orientation of the acceleration vector with respect to a set of coordinate axes. Analysis of frequency components can be achieved through spectral analysis, but we urge that caution should be practiced when comparing different spectral representations, Figs. 1-4.

Data decimation can be used to limit the amount of data an investigator should process for post-flight experiment analysis. The reduced acceleration levels resulting from decimation may restrict the usefulness of this technique, depending on the specific needs of the investigator. Cross-correlation analysis is a viable means of assessing causal relationships between residual accelerations and experimental response to accelerations. This method is useful for experiments sensitive to transient accelerations and to oscillatory disturbances.

As we increase our understanding of the acceleration environment of orbiting space laboratories, we will be better able to design and locate low-g experiments to obtain the best results possible. Most experiment sensitivity limits used at present are derived from numerical modelling or order of magnitude estimates. With a knowledge of low-g experiment results and the environment in which these results were obtained, we can revise tolerance limits, identify "normal" acceleration levels, and decrease further the amount of accelerometer data that must be accessed by investigators after future missions.

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Table 1. Orbiter natural frequencies, after Cooke et al. [12].

Natural Frequency	Structure
0.43 Hz	Cargo Bay Doors
0.57 Hz	Cargo Bay Doors
0.86 Hz	Cargo Bay Doors
1.2 Hz	Cargo Bay Doors
1.5 Hz	Cargo Bay Doors
2.1 Hz	Radiators
2.4 Hz	Radiators
3.5 Hz	Fuselage Torsion
	Wing and Fin Bending
5.2 Hz	Fuselage First Normal Bending
7.4 Hz	Fuselage First Lateral Bending

Table 2. Outline of data reduction plan.

Level One

1. Pre-flight identification of acceleration sensitivity to determine frequency and magnitude ranges of interest and experiment tolerance limits.

2. Pre-flight identification of times at which the experiment is liable to be most vulnerable, i.e., some experiments may be most sensitive at specific stages (e.g. protein crystal growth during the nucleation stage).

3. Preliminary post-flight analysis of experimental results to identify times when unexpected results occurred that may be related to perturbations in the residual acceleration environment of the laboratory.

Level Two

1. Selection of time windows of interest using a threshold detection routine based on sensitivities identified in Level One, Step 1 above.

2. Use of data decimation techniques, when appropriate, to reduce the number of data points needed to evaluate lengthy windows of data.

3. Specific analysis of windows of data identified in Level One and first step of Level Two, including estimation of mean and mean squared values, determination of the acceleration vector orientation, and spectral analysis to investigate the magnitude of the frequency components for the specific time window of interest.

4. Evaluation of accelerometer data in conjunction with experimental results to identify causal relationships and revise sensitivity limits.

Figure Captions

Fig. 1. Window of accelerometer data collected during the SL3 mission (Bell Miniature Electro-Static Accelerometer, f_s=300 Hz, nominal 50 Hz lowpass filter). The disturbance was probably caused by a thruster firing or a local acceleration source within the Spacelab. a) Acceleration vector magnitude. b) Combined spectral density for the three recording axes. Note frequency components at 5, 12, and 17 Hz.

Fig. 2. Window of accelerometer data from SL3 probably caused by crew activity within the Spacelab. a) Acceleration vector magnitude. b) Combined spectral density for the three recording axes. Note the dominant 17 Hz component.

Fig. 3. Differences in magnitude level result from the use of different sampling rates and/or filter cut-offs. a) Window of SL3 accelerometer data (y-axis of Fig. 1). b) Same data window with 13 Hz lowpass filter applied. Note difference in magnitude between two plots.

Fig. 4. Spectral densities of twenty successive SL3 time windows. Note varying strengths of 5 Hz, 12 Hz, 17 Hz, and 34 Hz components.

Fig. 5. Example of data decimation. a) Original SL3 time series of 65536 points (218 seconds). b) Spectral density of a). c) Time series decimated 16×; 5 Hz lowpass filter applied. d) Spectral density of c). Note decrease in magnitude from original series to decimated series.

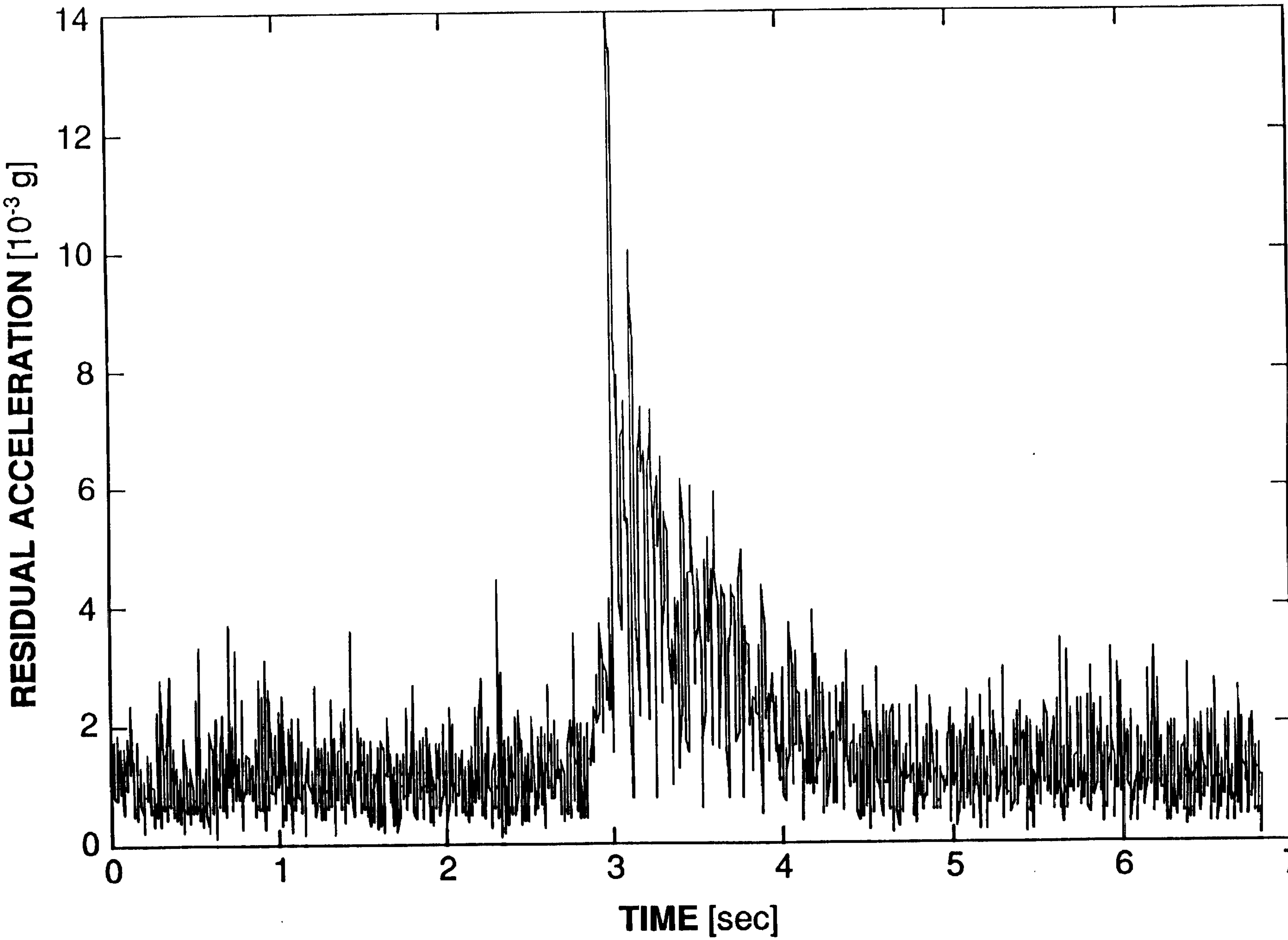
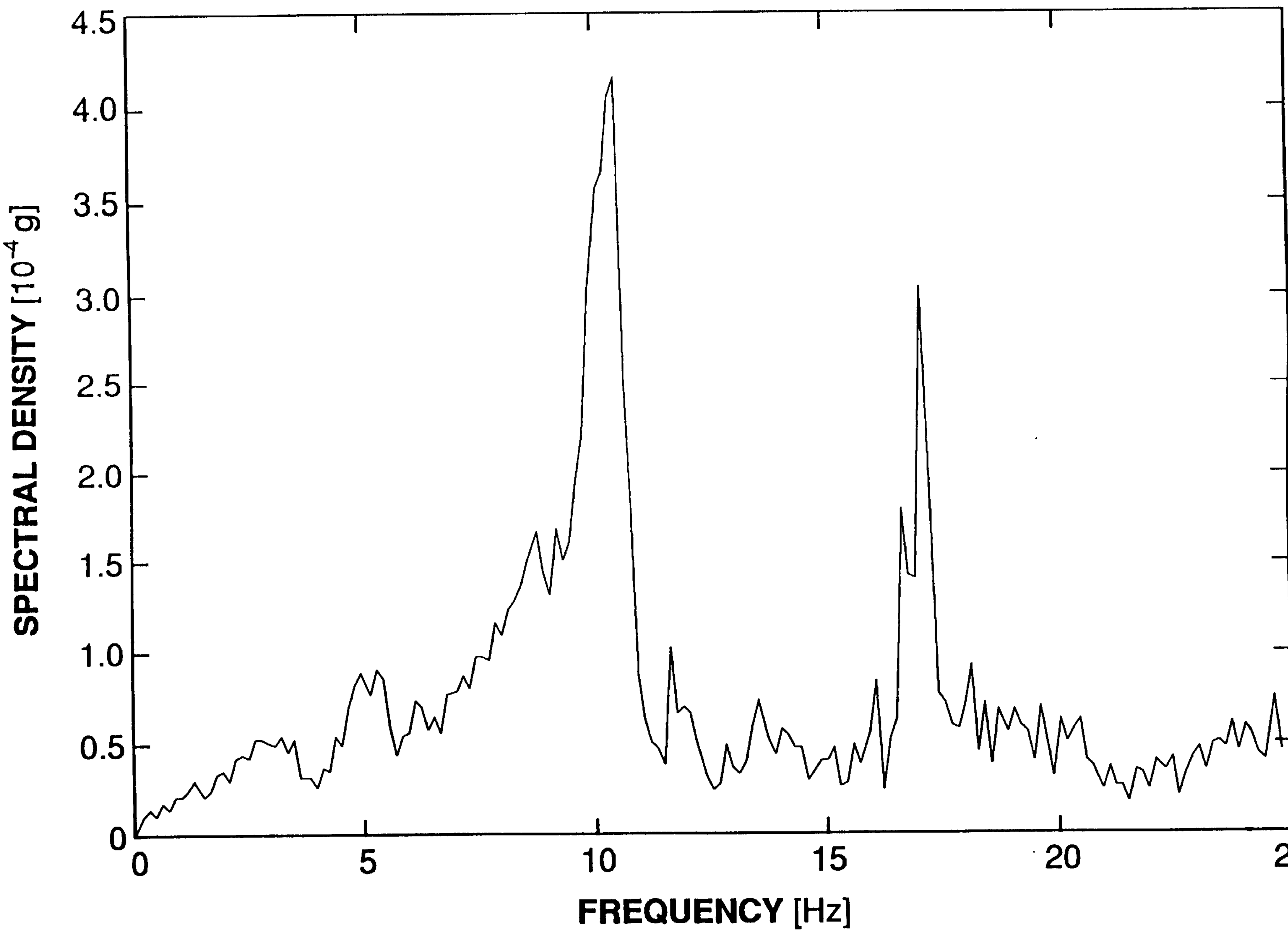

RESIDUAL ACCELERATION [10-3 g]
14
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
TIME [sec]

FIG. 1a



SPECTRAL DENSITY [10^-4 g]
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
0
5
10
15
20
25
FREQUENCY [Hz]

FIG. 1b

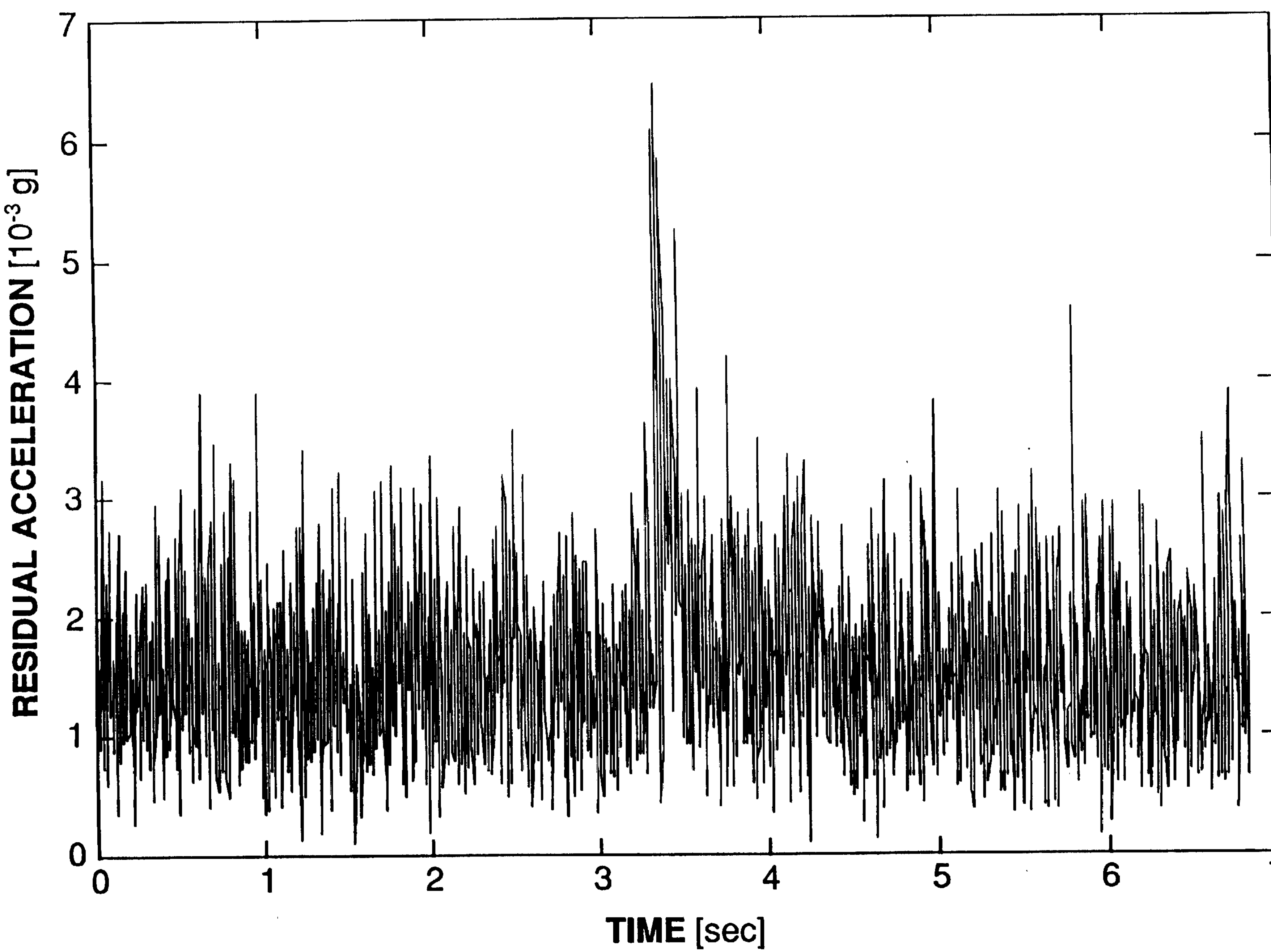


FIG. 2a

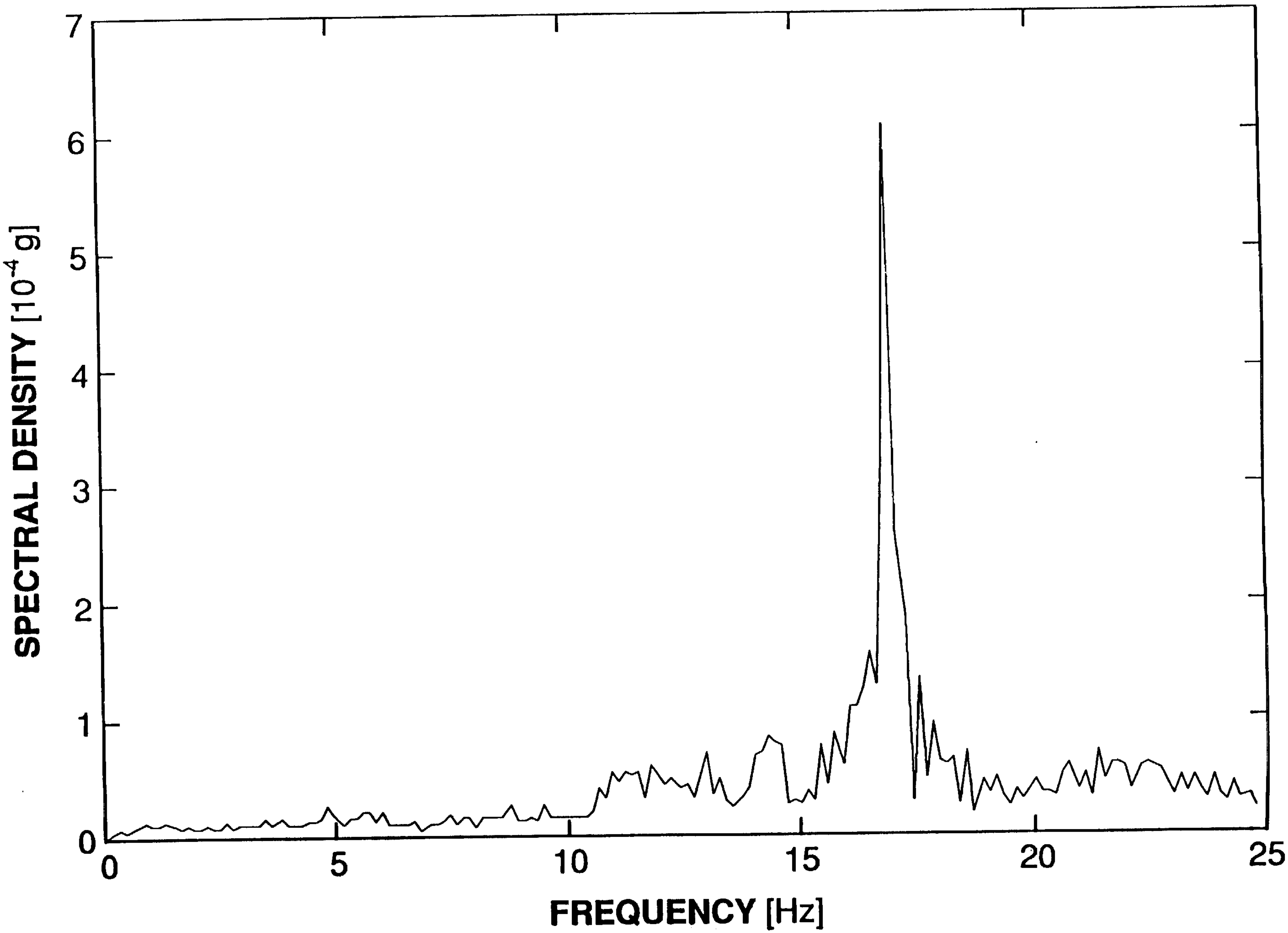
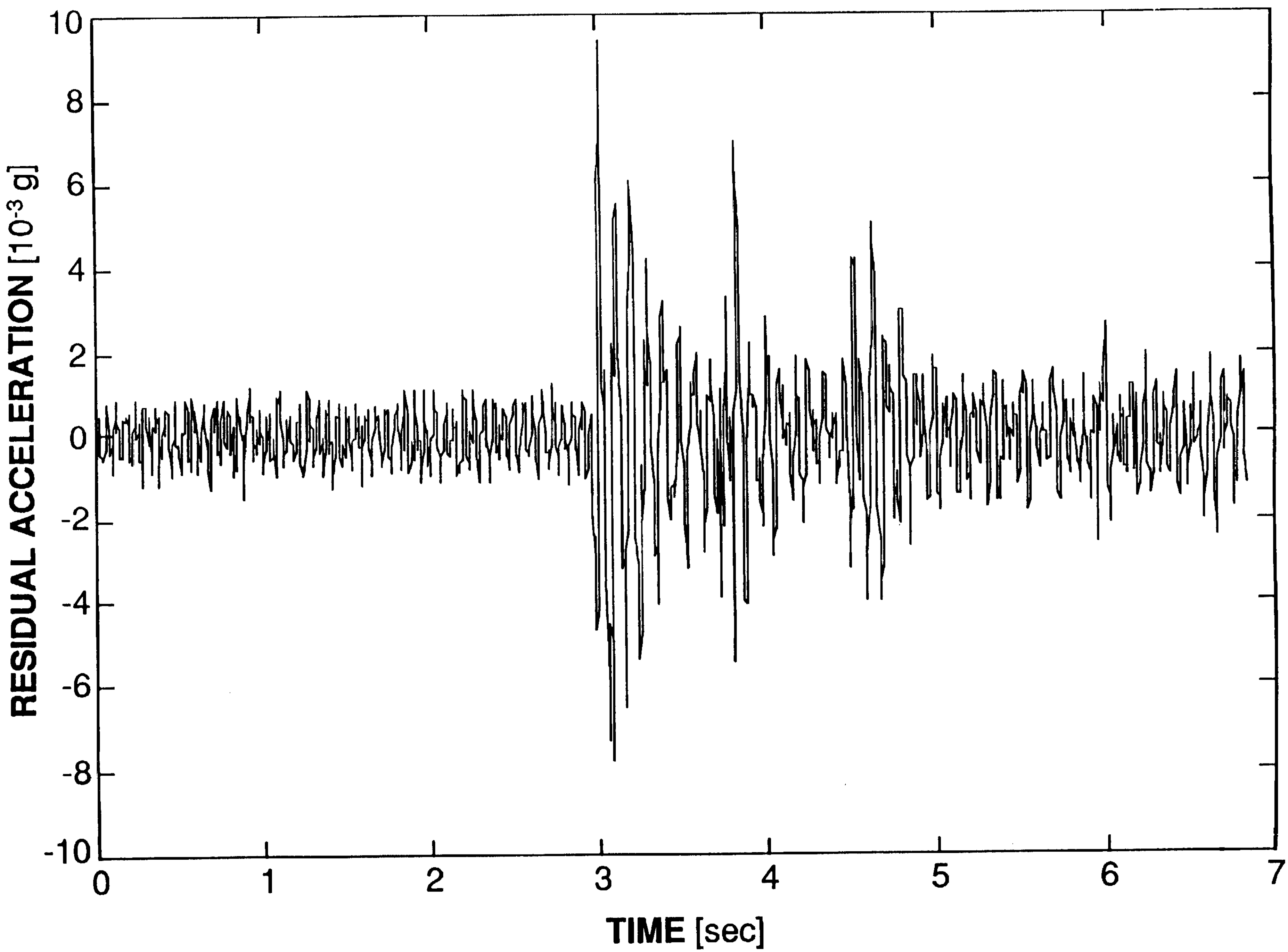


FIG. 2b


RESIDUAL ACCELERATION [10-3 g]
TIME [sec]
10
8
6
4
2
0
-2
-4
-6
-8
-10
0
1
2
3
4
5
6
7
FIG. 3a

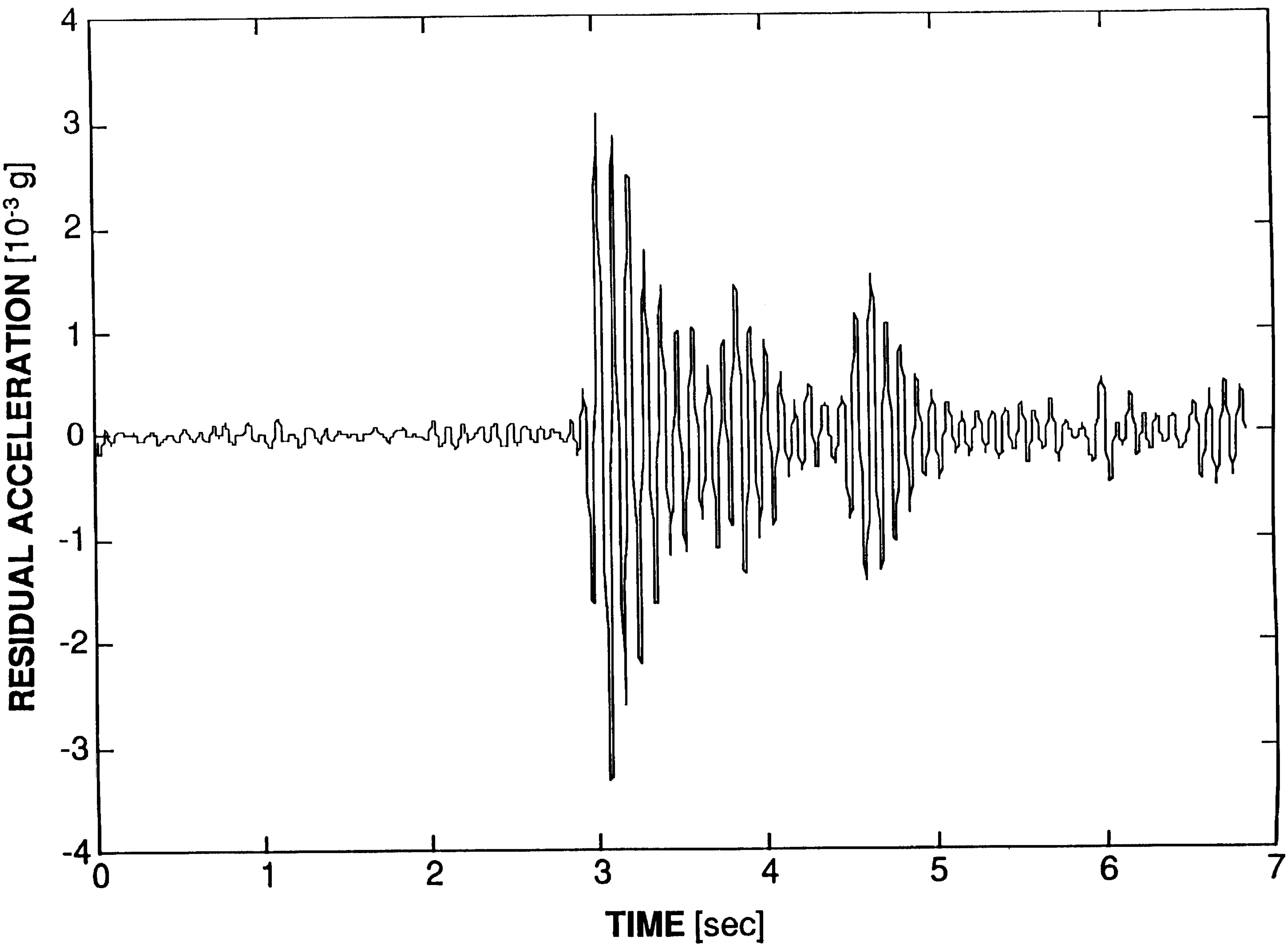
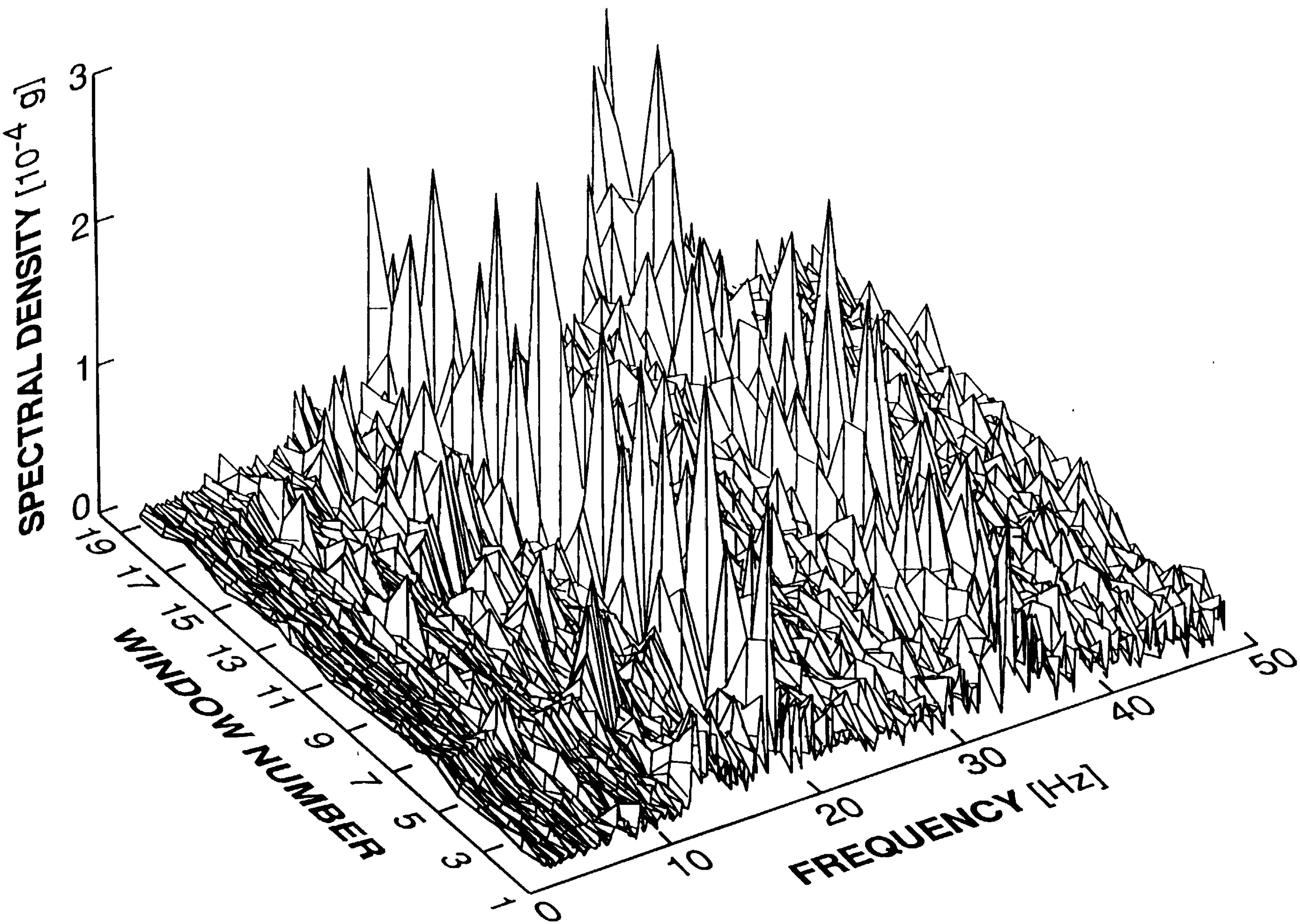
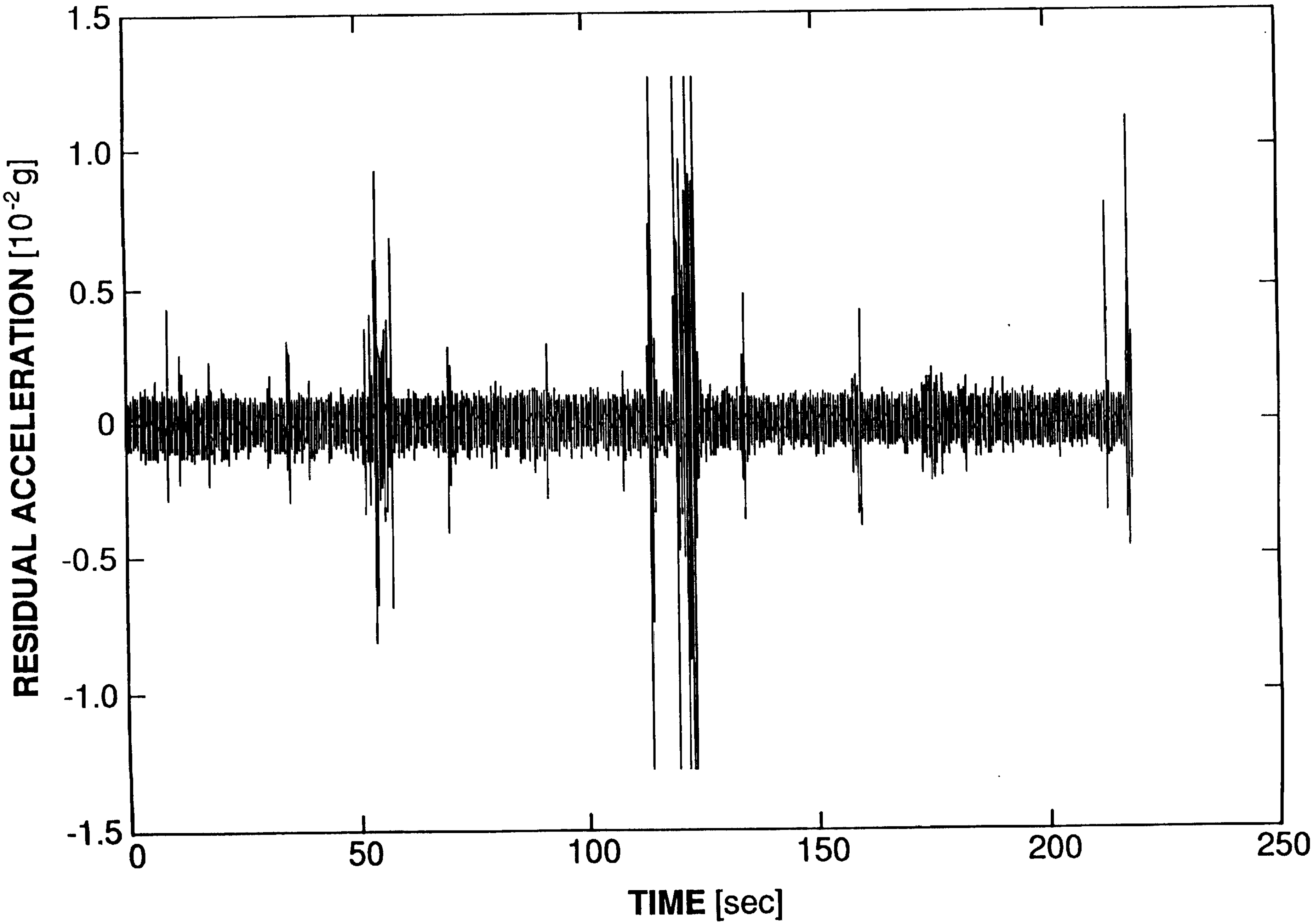


FIG. 3b



SPECTRAL DENSITY [10^{-4} g]
0
1
2
3
WINDOW NUMBER
19
17
15
13
11
9
7
5
3
1
FREQUENCY [Hz]
0
10
20
30
40
50

FIG. 4



RESIDUAL ACCELERATION [10-2 g]
1.5
1.0
0.5
0
-0.5
-1.0
-1.5
0
50
100
150
200
250
TIME [sec]

FIG. 5a

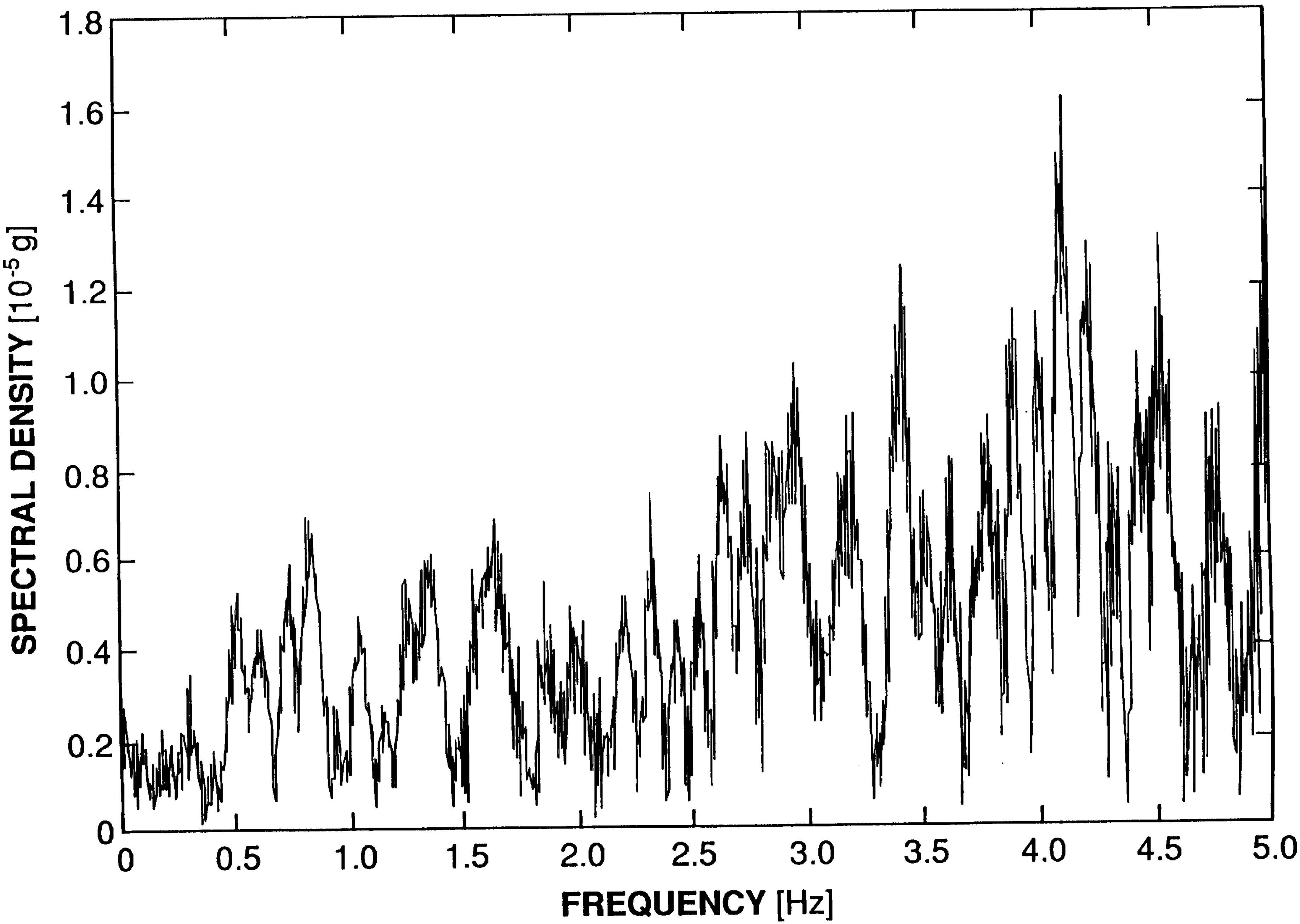

1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
SPECTRAL DENSITY [10-5 g]
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
FREQUENCY [Hz]

FIG. 5b

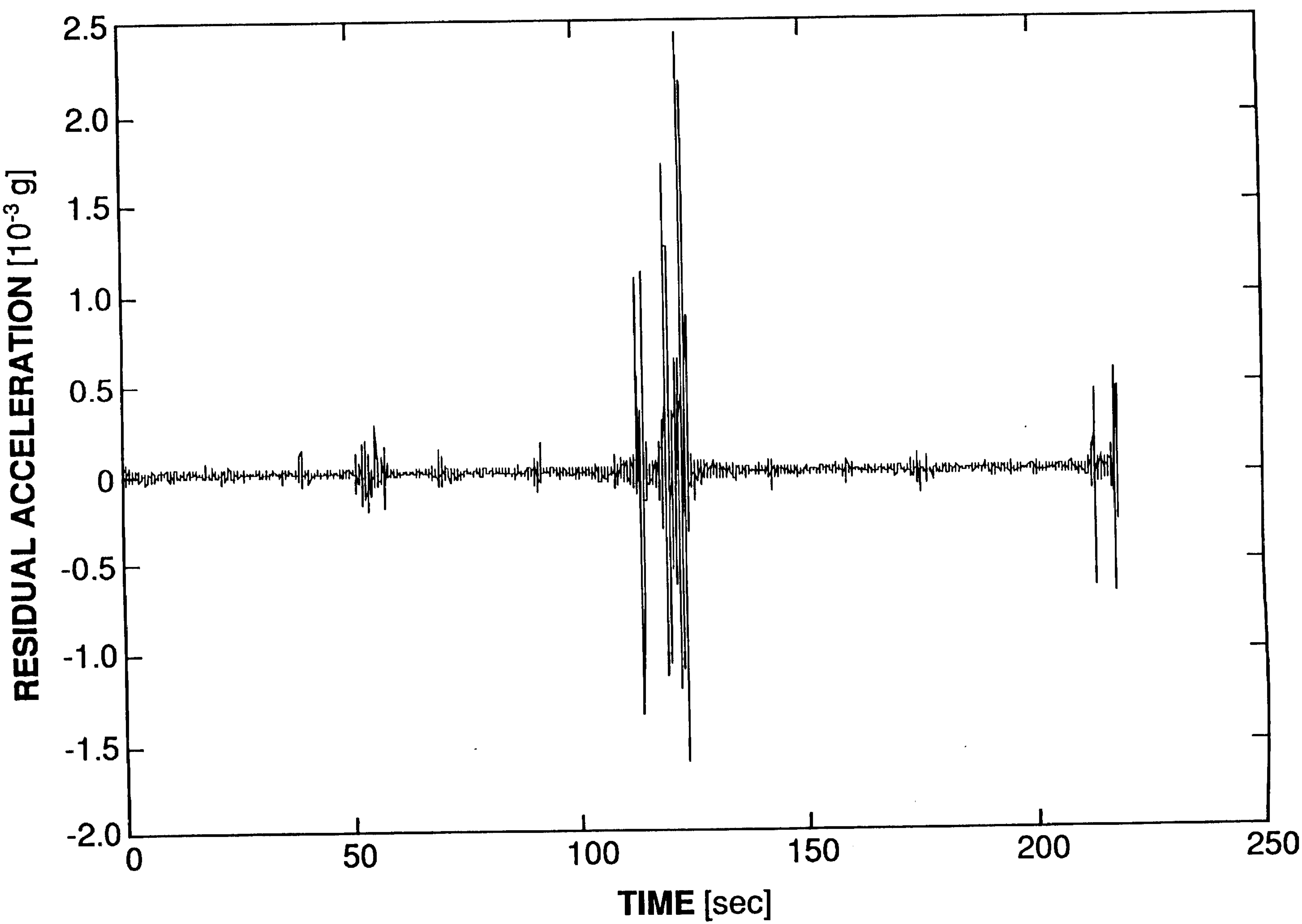

RESIDUAL ACCELERATION [10-3 g]
2.5
2.0
1.5
1.0
0.5
0
-0.5
-1.0
-1.5
-2.0
0
50
100
150
200
250
TIME [sec]

FIG. 5c

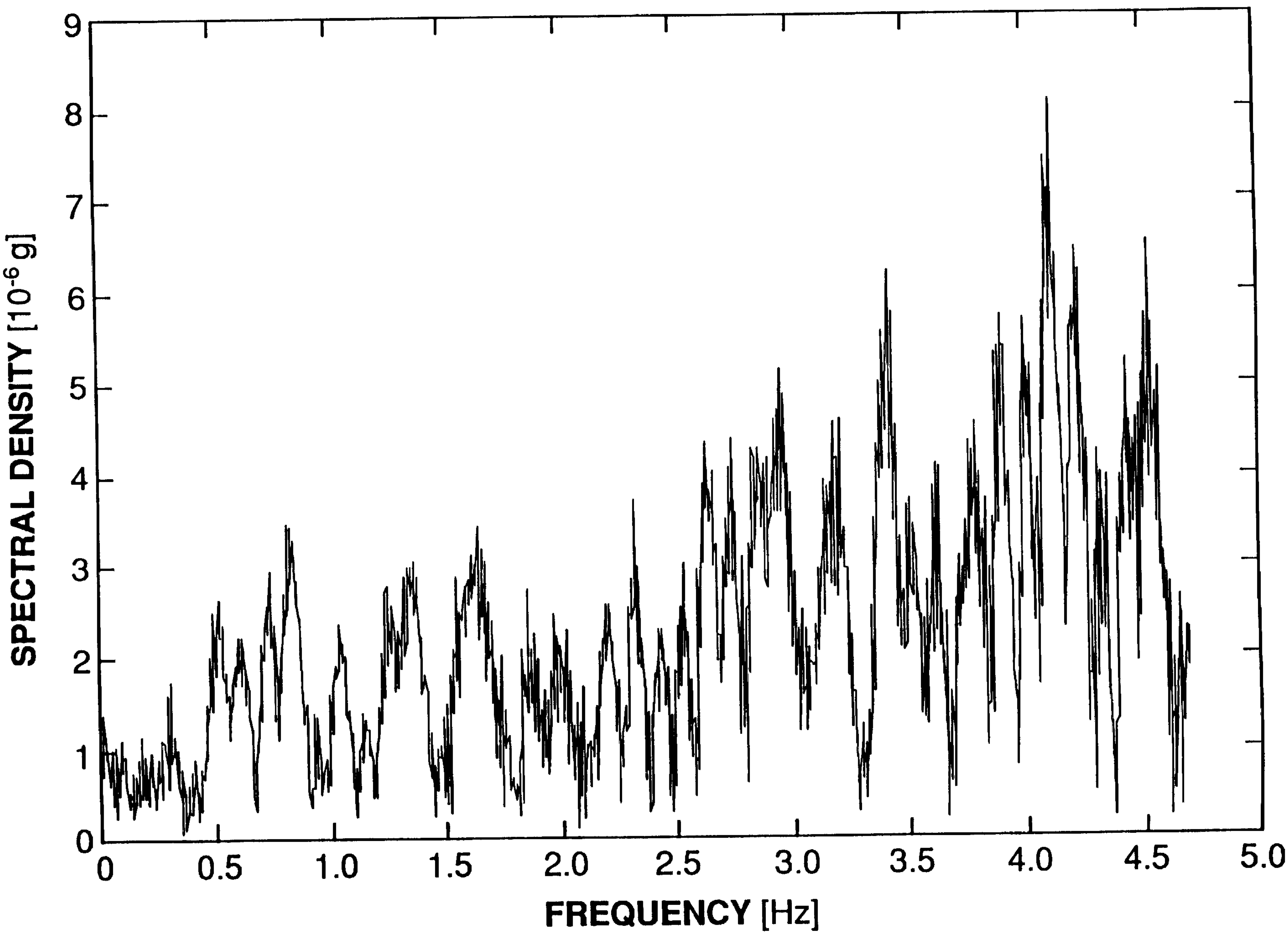

SPECTRAL DENSITY [10-6 g]
9
8
7
6
5
4
3
2
1
0
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
FREQUENCY [Hz]

FIG. 5d